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Comparative Assessment of Pipeline Plough Performance Prediction Models Against Field Experience in Sand

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ABSTRACT

The ability to predict offshore pipeline plough performance (e.g. tow forces and progress rates) in a variety of ground conditions is an important part of project planning. This may be estimated based upon experience from nearby locations or similar ground conditions, but existing empirical plough force prediction models are available and recent updates have been made. With the increasing use of digital data, it is hoped that greater reliance can be placed on these models and this process can be automated and integrated into Geographic Information System type applications. This paper uses real offshore plough data from three trenching projects in sand to compare plough performance prediction models.

KEY WORDS: Pipelines; pipeline installation; ploughing; performance models; sand.

INTRODUCTION

To allow appropriate planning for offshore pipeline ploughing installation campaigns it is necessary to reliably predict tow forces and advance rates prior to undertaking works, or at the tendering stage. This is not only important for planning, but also in selecting appropriate tow vessel support and deciding the approach to ploughing i.e. can the ploughing be undertaken in a single pass whilst minimising tow forces and maintaining adequate progress rates, or are further passes required. A multi-pass approach may be adopted where although the design trench depth could be achieved in a single pass, trenching is undertaken in two or more passes with an initial shallow trench depth followed by trenching to the final design depth (Machin, 1995). A multipassing approach may seem counterintuitive because of the associated additional plough handling time and the requirement of pulling the plough across the seabed more than once, but this can be more efficient and save time when compared to a single pass.

The potential benefits of a multipass approach are demonstrated by Eq. 1 (Cathie and Wintgens 2001) where the passive pressure component of tow force (*F*) is shown to increase with depth (*D*) cubed and there is a rate dependent term or potential for tow forces to increase with increasing plough velocity (*v*). This latter term is dependent again on the depth of the plough share but also on the soil permeability and its potential to dilate (relative density, or unit weight γ and depth of ploughing) during shearing, resulting in low pore pressures and increased effective stress (Lauder et al., 2012).

$$F = C_w W' + C_s \gamma D^3 + C_d v D^2 \quad (1)$$

Eq. 1 also has terms to account for the interface friction between sand and the plough e.g. C_w which is analogous to tanδ (where δ is the soil-plough interface friction angle) and *W'*, the buoyant weight of the plough. C_s is a "static" empirical parameter that reflects the shape of the plough share and the passive resistance characteristics of the ground. C_d is a rate dependent parameter that accounts for pore pressure equalisation and the potential for dilation. Typical values for these parameters are presented in Cathie and Wintgens (2001) where their magnitude has been determined from analysing real plough performance records. This would seem an appropriate approach, but it is actually difficult to separate out the steady state velocity dependent and static components from real ploughing records since plough tow force is only generated when the plough is advancing. Also, precise soil data may not be known along the entire route with investigation points typically taken at 1 km spacing. This difficulty in deconvolution is reflected for instance in anecdotal evidence in the industry of a reluctance to use existing published C_s values for loose sand.

Due to these concerns it was previously decided to undertake scaled model based 1g plough testing to investigate the validity of the existing empirical parameters. Model plough testing has the ability to separate out the various terms i.e. interface friction can be investigated in a shear box and the static or passive term can be investigated by testing in dry sands to remove the velocity dependent effects. Model testing also allows strict control of sand bed preparation using well characterised sand (Lauder, 2011). Scaling effects that may influence results can be overcome by modelling of models (i.e. testing at various scales) or using geotechnical centrifuge techniques at elevated g levels (Robinson et al., 2019) where the effective stresses in the soil match those at prototype, or during full scale ploughing operations.

This paper looks at the effectiveness of modifications to the Cathie and Wintgens (2001) approach where new empirical parameters were derived from careful model plough testing at 1g (50th, 25th and 10th scale) (Lauder et al., 2013) and later verified at 50g for a 50th scale model. This is compared with the original model and one of similar form tuned to the specific performance of the actual ploughs used in the case studies.

To test the derived parameters, real field data was used from three different full-scale ploughing operations in sand using the Saipem PL2 and PL3 ploughs. PL2 is smaller and has a lower submerged weight than PL3 but their share geometry is similar. PL2 and PL3 ploughs are both equipped with a forecutter A forecutter is a pre-plough share mounted on the beam in front and above the main share (see Fig. 1). A forecutter has been shown by Lauder et al. (2013) to be beneficial in reducing the rate effect but has a negative impact on the 'static' component of tow force but is of overall benefit in reducing the tow force during ploughing.

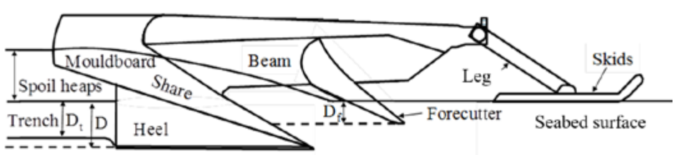

Fig. 1. Schematic of model pipeline plough with forecutter shown during trenching.

IMPROVEMENTS TO THE EXISTING EMPIRICAL MODEL

Lauder (2011) embarked on a comprehensive scaled model study of plough behaviour with a view to investigating and improving the empirical parameters determined by Cathie and Wintgens (2001) as applied in Eq. 1.

The form of Eq. 1 was found to be generally appropriate but that the values of C_s and C_d varied from those proposed. For example, Fig. 2 highlights how C_s does not appear to vary significantly with increasing relative density which is at odds with the large variation in values suggested by Cathie and Wintgens (2001). The no forecutter case is not relevant for PL2 and PL3 but is shown for completeness since this plough configuration was also investigated.

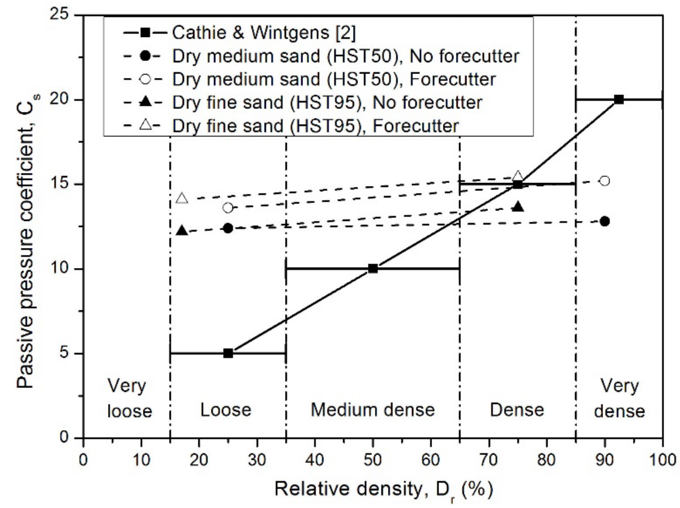

Fig. 2. Comparison of C_s values from model tests in dry and saturated sands compared with Cathie and Wintgens (2001) guidance values.

For such a large deformation event it is not surprising that the relative density has a reduced influence over soil resistance during ploughing. This is because soil resistance is dominated by post-peak behaviour due to averaging of shear strain over the numerous regular shear planes which are formed during ploughing. This would also suggest that there have been difficulties in deconvoluting real plough behaviour with attribution of incorrect force components to the frictional, static and rate dependent terms. Once the frictional and static components have been determined through shear box interface and model testing in dry sand it is then possible to investigate the rate effect term through saturated tests at various ploughing speeds and depths in different soils at 1g (Lauder, 2011). In the centrifuge, only one soil was used but the viscosity of the pore fluid was manipulated so the apparent permeability could be artificially changed to allow the simulation of variability in soil conditions (Robinson et al., 2019). From the study of rate effects it was found that the rate effect term proposed by Cathie and Wintgens (2001) led to over prediction of the rate effect (Fig. 3). There was also no specific separation of values for ploughs with, or without forecutters.

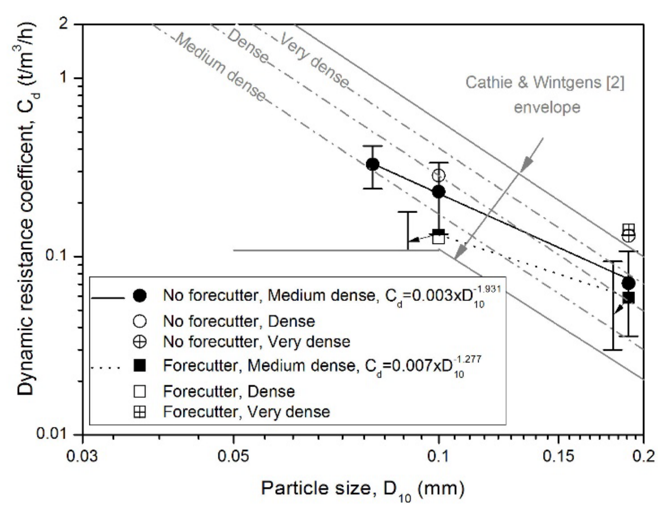

Fig. 3. Average C_d values from tests at various relative densities both with and without a forecutter (for clarity error bars representing data range is shown only for medium density tests and shown offset for forecutter case).

As the range of soils investigated in the rate effects study was not as comprehensive as that in the original Cathie and Wintgens (2001) data base, simple equations were used to represent the behaviour over the range of permeabilities tested:

$$C_d = 0.003 \times D_{10}^{-1.931} \quad (2)$$

$$C_d = 0.007 \times D_{10}^{-1.277} \quad (3)$$

Where the soil D_{10} (defining the proportion of finer particles in a sand) is used to indirectly determine the soil permeability as proposed by Hazen (1910). Eq. 2 reflects the behaviour for a plough without a forecutter and Eq. 3 with a forecutter; both in medium dense sand. C_d has units as shown in Fig. 3 so Lauder et al. (2013) modified this to a dimensionless form:

$$F = (C_w W' + C_s \gamma' D^3)\left(1 + C_{dn}\frac{svD}{c_v}\right) \quad (4)$$

Where C_{dn} is the dimensionless form of C_d, s is a soil dilation parameter that can be determined from a shear box test and c_v is the soils coefficient of vertical consolidation which reflects permeability and potential for volume change during shear. Although this form is dimensionless it is not easy to determine the required input parameter (s) from field testing and sampling and would potentially require in-situ dissipation testing (if possible) or more specialist lab testing. Due to the difficulty in practicably determining the input parameters for Eq. 4, comparison with field data has been accomplished using Eq. 1 in its original form, but with the improved input parameters (e.g. Fig. 1 & Eq. 4) determined by Lauder at al. (2013) and compared with the original parameters proposed by Cathie and Wintgens (2001). Most plough operators though have their own ploughing models tuned to the performance of their ploughs. In this case a relationship of the form shown in Eq. 5 was also used for comparison.

$$F = K_1 W' + K_2 D^2 + K_3 v D^2 \quad (5)$$

Which is of a similar form to Eq. 1 with K_1 to K_3, being analogous to C_w, C_s and C_d. It is noteworthy that the "static" or passive term is squared rather than cubic and the K values may differ from the C values, although K_1 which refers to the interface friction term should be the same as C_w. The passive term also lacks separate recognition of the relative density or unit weight of the soil encountered. Instead relative density is recognised indirectly in the selection of K_2 which varies with peak friction angle based upon previous experience and finite element modelling studies, Eq. 6.

$$K_2 = a\emptyset'^2_{peak} + b\emptyset'_{peak} - c \quad (6)$$

Where a, b and c are empirical fitting parameters proprietary to Saipem.

Again, this is similar to the variation seen in Fig. 2. K_3 is also determined based upon the peak friction angle which is assumed to be included to account for the potential for dilation or contraction with changes in relative density and thus increased or reduced rate effect potential (and thus similar to s).

$$K_3 = A \times D_{10}^{-2} \quad (7)$$

Where A is an empirical fitting parameter, also related to $\emptyset'_{peak}$ (not shown for proprietary reasons).

CASE STUDY 1

It should be noted that real plough data is "noisy" due to the apparently irregular motion of the plough caused by positional and tow line effects. To remove this, all data shown for the following case studies have been smoothed by 50 point adjacent averaging to aid comparison.

Case Study 1 consists of a 12 km long pipeline section where ploughing was undertaken in fine loose to very loose sand (approx. 0-1 m Below Seabed Level, BSL) overlying dense to very dense sand (approx. 1-2 m BSL) underlain by medium to dense sand. Ploughing was undertaken in a single pass with depths along the run varying from 0.92 to 2.1 m (average 1.6 m) with average plough progress rates of 264 m/hour. The maximum tow force recorded during operations was 298 tonnes (average 246 tonnes). Investigation by CPTs was undertaken at 1 km intervals with additional shallow vibrocores taken at similar intervals. Data from the CPTs and vibrocore samples were used to infer the information required to populate the various ploughing models with parameters such as peak friction angle being based upon relative density determined from CPT. Particle size, D_{10} was obtained directly from sieve analysis of the sampled soil and varied between 0.062 to 0.072 mm for the sand with vibrocore descriptions also referring to the presence of silty sand.

Fig. 4 shows the results of the various plough prediction models compared with the measured tow force from the plough itself. It is clear that there is significant variation between the various prediction models used.

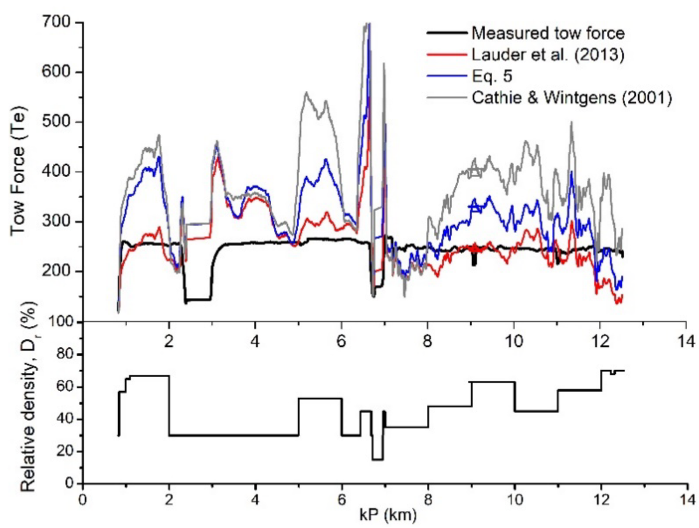

Fig. 4. Case Study 1 plough performance in terms of tow force along the route. The relative density shown is the average interpreted from seabed surface to plough tip level.

The original Cathie and Wintgens (2001) approach appears to significantly over predict the plough tow force by up to a factor of 2, especially in the zones associated with higher relative density. The performance of Eq. 5 is somewhat better but again with a tendency to overpredict tow force by 40 to 70%. Generally though, the Lauder (2013) modifications to the parameters in Eq. 1 seem to perform better and is less sensitive to apparent change in relative density and the subsequent excessive effect on the prediction of the rate component. The static terms (C_s & K_2) are dependent on relative density/peak friction angle and thus can vary throughout the plough run whereas the Lauder (2013) approach showed that this was independent or insensitive to the in-situ relative density and that this value should be fixed, or vary to a minimum extent. Also, the rate effect terms in Eq. 5 and the Cathie and Wintgens method vary with relative density/peak friction leading to the observed significant overprediction. The Lauder (2013) approach only investigated a limited range of densities but did separate out the influence of a forecutter which the other methods do not. Thus, whether it is a fair comparison or not, Eq. 3 was used for rate effect prediction and seems to give the best overall result.

It is acknowledged that if the full improved Lauder et al. (2013) model had also included a dilation potential parameter (*s*), assuming it were possible to determine this for the Case Study 1 site, may have also overpredicted tow force. It is however noted that the fully modified form of Eq. 4 includes the rate effect term as a multiplier on both the static and interface terms (to acknowledge changes in effective stress with ploughing speed) whereas the other approaches treat it as an additive term. Thus, the lack of data to determine *s* and the use of Eq. 3 may be accidentally fortuitous in this case, although this generally suggests that the rate effect response at this site is relatively insensitive to abrupt changes in relative density and dilation potential and explains why the two methods give significant overprediction of tow force.

As mentioned, the dense to very dense fine sand encountered may be expected to dilate significantly given the predicted high rate effects but in this case appears to be relatively insensitive to the relative density, although the rate effect component is 2 to 3.5 times the static component of the various methods (Fig. 5). This may be in part due to the complicated nature of the ground encountered i.e. loose sand over dense sand where plough behaviour is controlled by an inclined failure envelope that passes from the plough share tip at depth to the seabed surface. Thus, if the soil properties only at the plough share tip level were used to model behaviour there would have been even greater over prediction from Cathie and Wintgens. Eq. 5 highlights the need for careful interpretation of soil properties from the seabed to the target plough depth to cover the full extent of the failure surface.

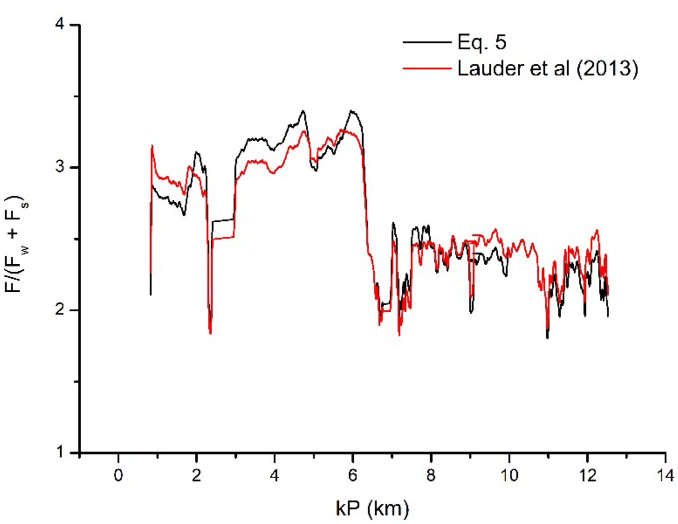

Fig. 5. Variation of the rate effect multiplication factor along the route highlighting the consistency in static component predictions.

These results suggest there is some room for improvement in plough prediction models especially in fine grained sands with increasing silt content with respect to the rate effect component. Fig. 5 shows that adoption of either Eq. 4 or Eq. 5 results in similar rate effect factors relative to the static components (F_w and F_s) of tow force (F). This then suggests that the static components predicted by the Lauder et al. (2013) modification of Eq. 1 and the method to determine K_2 in Eq. 6 are similar which may suggest appropriate representation of true plough behaviour and general confidence in the ability to predict the static components.

It is noted though, that Eq. 5. and Eq. 6. do not directly acknowledge the in-situ unit weight of the soil which is a departure from the other methods shown. This form also varies from the other approaches in that both static and rate effects components vary with D^2 whereas all other approaches use D^3 as verified by Lauder (2011) for both static and rate effects components (Lauder et al., 2012). The use of D^2 would seem more appropriate if obvious and easily measurable plough geometry variations with depth were introduced into the analysis. For example, Robinson et al. (2016) and Robinson et al. (2017) have proposed including plough width terms in the analysis of the simpler geometry of cable ploughs and thus reducing the magnitude of the empirical term C_s through the inclusion of known geometry controls.

With respect to rate effects, Lauder (2011) only investigated three sands of varying permeability or particle size distribution (D_{10} = 0.19-0.08 mm) which were coarser than those encountered at this site. The use of the dilation potential, *s* mitigates this limitation to some extent, but this would require more routine use of specialist testing to determine the dilation potential (and c_v). Ideally it would also be more appropriate to have experience of ploughing across a wider range of soil permeabilities and densities to verify and validate the assumptions in all three approaches which have variable performance predictability in fine grained and potentially silty sands. Cathie and Wintgens database covers a wider range of soils but this shows significant scatter and as found by Lauder (2011) previously and shown here has a tendency to overpredict rate effects where peak friction angle alone, or with particle size as an analogue for permeability, is used to infer dilation potential.

The other noteworthy points along the route occur between KP 3 and 4 where the results from all of the methods over predict performance but to a very similar degree. This section appears to be a zone of loose sand where limited dilation or contractive behaviour may occur leading to low rate effects and a potential reduction in the static term, depending on how this is formulated (i.e. positive pore pressure generation and reduction in effective stress).

CASE STUDY 2

Case Study 2 consists of a 2.5 km long pipeline section where ploughing was undertaken in fine medium dense to very dense sand (approx. 0-5m BSL). Ploughing was performed in a single pass with depths along the run varying from 1.18 to 1.66 m (average 1.39 m) and average plough progress speeds of 576 m/hour. The maximum recorded tow force was 229 tonnes. This is obviously shallower than in Case Study 1 with significantly greater average speed and reduced tow forces. This potentially highlights the rate effects that may have been associated with the Case Study 1 site due to the fine grained silty sand, however as the plough depth has a squared or cubed effect on tow force the difference will be a significant control on performance.

This site also has much more consistent sand density with depth, typically varying between a relative density of 70 to 80%, making interpretation of soil properties over the zone of plough influence easier. Ground investigation was undertaken with CPTs, near surface box samples and piston coring at focused locations along the route, rather than necessarily at regular intervals. Particle size, D_{10} was obtained directly from sieve analysis of the sampled soil and varied between 0.13 and 0.15 mm which is coarser than in Case Study 1.

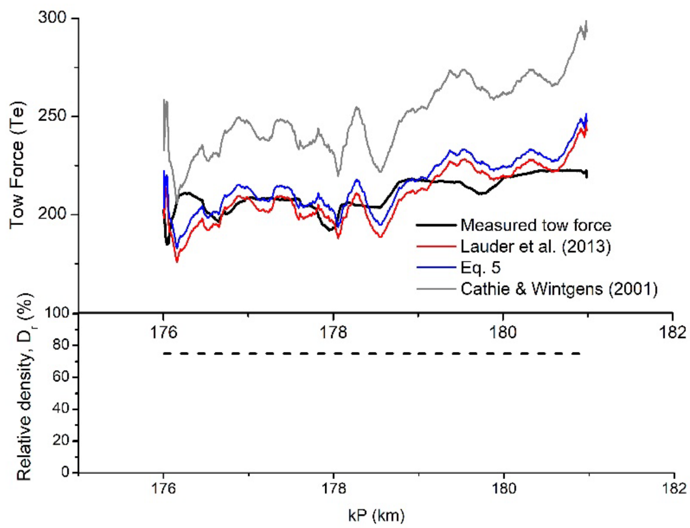

Fig. 6. Case Study 2 plough performance in terms of tow force along the route. The relative density is shown as a dotted line due to limited CPT data along the short plough leg shown.

The results in Fig. 6 generally show better predictions for all of the methods in this fine to medium grained sand where permeability and subsequent rate effects will be reduced. The original Cathie & Wintgens model still tends to over predict by up to a factor of 1.3 which is thought to be due to the original value of C_s being too high and varying too much with relative density (which increases tow force predicted by Cathie and Wintgens (2001) method in this dense sand site) and the rate effect term C_d varying too greatly with relative density (as highlighted by previous research). The method outlined in Eq. 5 also performs well here as it appears to be good at predicting the static component of resistance but has a tendency to overpredict the rate effects in the finer grained or silty sands as shown in Case Study 1. Further detailed comment on the specific variability of the results is not possible due to the lack of CPT data along this short ploughing leg.

CASE STUDY 3

Case Study 3 consists of a 24.6 km long pipeline section where ploughing was undertaken in fine to medium very dense sand (approx. 0-1.5 m BSL) overlying dense sand (approx. 1.5-4 m BSL). Ploughing was performed in a single pass with depths along the run varying from 0.59 to 1.95 m (average 1.195 m) and average plough progress speeds of 760 m/hour (range 70-1219 m/hour). The maximum recorded tow force was 232 tonnes which is similar to Case Study 2 although average progress rates are greater, and the average ploughing depth was slightly shallower.

This site also has a much more consistent sand density with depth, typically varying between a relative density of 90 to 95%, simplifying interpretation of soil properties over the zone of plough influence. CPT investigations were undertaken at 1 km intervals with additional shallow vibrocores taken at similar intervals. Particle size, D_{10} was obtained directly from sieve analysis of the sampled soil and varied over a wider range than the other two sites between 0.068 to 0.17 mm suggesting significant potential for investigating differences in rate effects across the site. The consistent relative density and variation in D_{10} makes this case study useful for investigating the soil permeability or particle size affects in isolation.

Fig. 7 shows similar behaviour to that seen in Case Study 1 and Case Study 2 where the methods outlined by Lauder et al. (2013) and Eq. 5 work well in the coarser grained soil. As the soil becomes finer, similar patterns of over prediction are seen as in the other two sites.

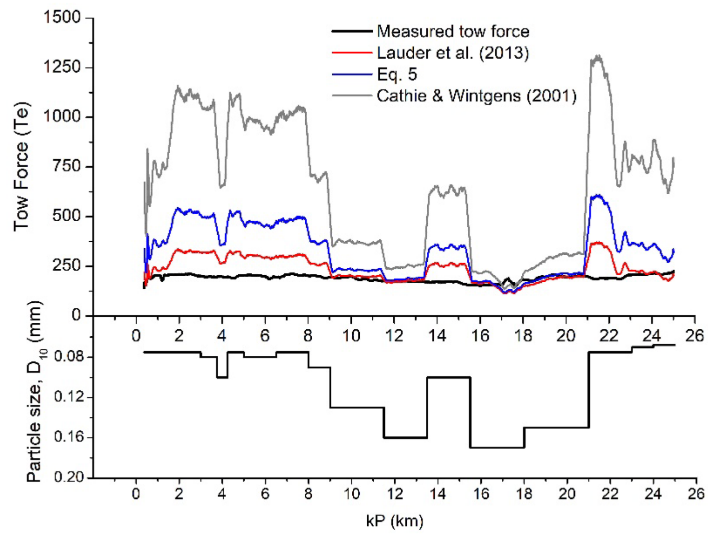

Fig. 7. Case Study 3 plough performance in terms of tow force along the route. This figure shows D_{10} variation since relative density across the site was relatively constant.

It is also noteworthy that although there is a relatively significant change in D_{10} (as opposed to near constant D_{10} and significant variation in relative density in Case Study 1) along the route, the measured tow force is relatively constant and insensitive to these apparent changes, which is similar to that previously found in Case Study 1 for the static term C_s. This stability of C_s is attributed to the large strain nature of pipeline ploughing and that the tow force reflects an average type behaviour derived from the continuous formation of new passive failure wedges ahead of the plough. This smooths the effects of excessive dilation on shear strength that might be expected for shallow ploughing where peak friction and dilation would be expected to control behaviour. This seems to be the case for both the passive and rate dependent terms in the measured plough data. Whereas the prediction methods do not seem to reflect this apparent smoothing of the rate effect components i.e. the rate effect component is still significant but is not as sensitive to velocity variations in the measured data.

FURTHER DEVELOPMENT AND OBSERVATIONS

This paper has shown that very different predictions of plough tow force and subsequently rates of progress can be arrived at, depending on the method of prediction used. In general, the improvements proposed to the original Cathie and Wintgens (2001) model perform much better. This paper though has highlighted that there is still room for improvement with respect to predictions of the rate effect components, particularly in low permeability sands with high silt content.

There are also issues with predicting the rate effect component at the extremes of relative density i.e. in loose and very dense sands. For example, the methods allow for dilation in the sand and reduction in pore pressure (increase in effective stresses) but do not allow for the opposite extreme where in loose or very loose materials effective stresses may reduce below in-situ due to contractive soil behaviour.

If this is going to be captured in the rate effect term then the form of analysis proposed by Lauder et al. (2013) in Eq. 4 seems more appropriate where the static terms are multiplied by the rate effect term i.e. recognizing the modification of effective stress regime in the passive and interface shearing due to plough progress rates. This form though has its own limitations and was consequently not used here. Firstly, the parameters require more specialised testing and may be difficult to determine for coarse grained soils. For example, there is a need to determine *s*, the dilation potential or state parameter which ideally requires specialist direct shear box testing. Alternatively, this could be derived directly from in-situ CPT in a similar manner to Eq. 5 - 7 where the dilation potential is reflected in determining the peak friction angle and assuming a critical state friction angle (or state parameter as per Robertson 2010). The coefficient of consolidation (c_v) may be determined from in-situ CPT dissipation testing but this is likely to be difficult in coarse grained soils due to the rapid dissipation times. The coefficient of consolidation itself relies on knowing the soil permeability and coefficient of compressibility, m_v ($m_v = 1/E_0$).

As used here simple analogues for permeability are based upon D_{10} derived from particle size distributions that are normally a standard laboratory test scheduled in pipeline route investigations. The compressibility though is more a difficult parameter to obtain, relying on specialist oedometer testing or the use of the continuous loading oedometer test, but again this will depend on the permeability of the sand which may be too high to achieve adequate results (Atkinson and Davison, 1990).

Near surface stiffness could be estimated based upon existing published relationships e.g. a square root relationship with effective stress but again such relationships are typically based on studies at significantly higher effective stress with minimum stresses of 100 kPa (Pestana and Whittle 1995). Lauder and Brown (2014) showed that there is significant variation in stiffness over the range of effective stresses encountered during ploughing and that significant variation occurs between different soils types. This highlights the potential issue of assuming standard parameters for stiffness and potentially permeability for tests or applications at very low effective stresses. The other concern with the use of Eq. 4 is that it assumes that the rate effects and changes in effective stress due to plough speed equally affect the passive resistance and the interface terms. This therefore also assumes the pore pressure regime is the same in advance of the plough share as it is at the interface of the plough. This may be a simplification that requires further investigation as pore pressures dissipate as the plough moves towards the inclined failure plane in advance of the plough.

It therefore seems there is room for further improvement and development of Eq. 4 which makes the required parameters easier to determine based upon in-situ testing (CPT) as per Eq. 5. The known width or shape of the plough with depth should also be included and the suitability of applying the rate effect to interface terms should also be investigated. This needs to occur over a wider range of soil permeabilities and densities. Undertaking these modifications will reduce the magnitude of the empirical parameters (C_s & C_{dn}) but also mean they will have to be re-assessed. This then is an incentive to understand all the controlling components on these parameters and hopefully allow them to be determined based upon directly measured parameters alone.

The level of analysis required here to investigate the performance of the models has also given insights into the challenges faced by geotechnical engineers undertaking pipeline route assessments and the need for high quality site investigation data, ideally comprising in-situ testing with corresponding soil samples at the same locations and spaced as closely as possible along the pipeline route. The focus of this testing should be near surface due to the shallow nature of trench depths. The data and reporting should also be designed to allow easy determination of relative density, in-situ friction angles and particle size distributions along the route. Caution should be exercised when interpreting the soil properties with depth especially where there is significant variation (e.g. Case Study 1) as the plough tow force is as a result of an inclined failure surface that projects from the plough share tip to the seabed surface with the full depth of the soil wedge influencing behaviour. This may seem obvious, but it should be accounted for during both specification of offshore route investigation, reporting and data interpretation if realistic performance estimates are to be obtained.

CONCLUSIONS

This paper has introduced why it is important for parties involved with pipeline ploughing and installation to be able to adequately predict tow forces and plough advance rates in sand, prior to site works. Several different methods for prediction are available in the public domain as well as those developed in-house for proprietary ploughs. The paper compares these various methods and highlights how they have evolved through the use of three Case Study sites in varying soil conditions (relative density and permeability). The paper highlights that generally the newer methods appear to make better predictions of the “static” or passive components of plough resistance but that there is scope for improvement in fine grained sands at the extremes of relative density. In these cases the prediction methods tend to attribute too great a rate effect contribution and overpredict tow forces.

The best performing model was based upon improvements to the Cathie & Wintgens model that reduced the sensitivity to relative density for both the passive and rate effect terms. An apparently more advanced version of this model was also considered but could not be applied in the case of real site works due to the requirement of a wider range of input parameters than can currently be obtained directly through in-situ testing or routine laboratory characterization. On this basis it has been identified that further development is required to develop this promising approach such that its input parameters can ideally be derived from in-situ testing alone, for example through determination of the in-situ state parameter. The current models on the whole also fail to acknowledge simple plough geometry controls such as width that is a fixed value at a certain depth that could easily be included in the analysis and remove unnecessary empiricism.

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